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LANDSLIDE PROCESSES IN SAPROLITIC SOILS OF A TROPICAL RAIN FOREST, PUERTO RICO

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ABSTRACT

Shallow soil slips, earth and debris slides appear to be a primary mechanism of hillslope denudation in the rainforest of eastern Puerto Rico. Annual rainfall in excess of 4,000 mm, and thick sequences (up to 20 m) of residual soils (saprolite) combine to produce these landslides. Shear-strength testing and observations of tension cracks indicate that landslides may start as tensile failure of saprolite material. The tension cracks provide avenues for rapid infiltration of rainwater and saturation of the underlying soil. During or shortly after intense and prolonged precipitation, shear failure then occurs as a result of pore-pressure buildup along zones of low permeability within the saprolite.

Tensile stresses in the unsaturated, low-density, upper saprolite zone range from 3 to 10 kPa, and mean seismic-refraction velocities are 476 +/- 127 m/s. Denser, clay-rich, less permeable saprolitic zones having mean seismic velocities of 1420 +/- 157 m/s represent zones that are commonly associated with perched ground water and are zones where excess pore-water pressure is most likely to trigger movement. These zones of translocated clay show marked density increases.

Slickensides are present in the saprolite along relict fractures and joints derived from the parent rock; they are common in quartz-diorite bedrock, and less so in marine-deposited volcaniclastic bedrock. The failure planes of many landslides have exposed these relict fractures and joints as slickensides, and landslides appear to move on these pre-existing planes of weakness in the saprolite. The largest landslides (areas greater than 20,000 m^2), however, are those that fail along saprolite-bedrock boundaries, which are zones of contrasting density and permeability within or at the base of the weathered profile.

INTRODUCTION

Landslides are a common problem in the Caribbean National Forest (CNF), an 11,330-hectare tropical rain forest in northeastern Puerto Rico (fig.1). More than 170 landslides have been mapped in this area using aerial photography and field observation (Guariguata and Larsen, 1990)(fig.1). Numerous sections of roadway have been damaged or destroyed, and lives have been lost as a result of these landslides. Rainfall, relict structures in saprolite, bedrock and soil type, and road-construction practices appear to be important controlling factors for landslide occurrence and location. These factors have been examined, and are discussed below, as part of a regional study of landslide hazards conducted by the U. S. Geological Survey in cooperation with the Planning Board of Puerto Rico.

Several investigators have described CNF landslides. St. John and others (1969) discussed the role of relict structures in residual soil as a control in small-scale landslides. Deere and Patton (1971) related landslide processes to intense rainfall and certain characteristics of the weathering profile. Sowers (1971) described various types of small slumps and earth slides as well as rock falls that hampered construction of a CNF highway begun in 1960. Most recently, in an island-wide map showing landslide susceptibility, Monroe (1979), classified the CNF as having moderate overall susceptibility, with a few areas of high and highest susceptibility.

SETTING

The CNF ranges in elevation from 100 to 1,075 m (meters) above mean sea level. Mean annual temperature and rainfall range from 26.5°C and 2,500 mm (millimeters) respectively in the lower elevations to 17.5°C and 4,500 mm at higher elevations (Brown and others, 1983). Intense precipitation may occur throughout the year but generally is associated with tropical depressions, hurricanes, or less intense tropical waves (Miller, 1965). These types of storms are most common between June and November and can result in 24-hour rainfall totals of more than 300 mm (Calvesbert, 1970).

Bedrock in the study area consists of marine-deposited andesitic to basaltic volcaniclastics of Cretaceous age (Seiders, 1971). In the upper Rio Blanco basin, these rocks have been intruded by the Rio Blanco stock, a light-gray, medium- to coarse-grained quartz-diorite that covers about 20 km (square kilometers) and is bounded by a metamorphosed zone extending 0.5 to 3.5 km into the surrounding volcaniclastics. Slopes in the CNF are mantled with a shallow [40 cm (centimeters)] but dense root zone (Brown and others, 1983) within the A and B soil horizons in the upper meter. This soil is derived from the underlying colluvium and and silt-clay saprolite. This sequence of saprolitic material overlies weathered and unweathered bedrock and ranges in thickness from 1 to 24 m (fig.2)(Dames and Moore, 1980; Larsen, 1989a,1989b; U. S. Dept. of Transportation, written comm., 1988).

METHODOLOGY

Data used in this study were obtained from bore-hole shear tests (BST); analyses of soil samples for grain size, Atterberg limits, moisture content, and bulk density; seismic-refraction surveys; landslide field surveys; and aerial photography. Bore-hole shear tests were conducted at depths ranging from 0.5 to 3 m, at several locations along slope profiles to measure in-situ shear strength (friction angle and cohesion). Detailed discussions of the BST are in Lohnes and Handy (1968), Lutenegger and Hallberg (1981), and Lutenegger (1987). Soil samples collected from the same depths as those used in the BST were analyzed as described by Lambe (1951).

Seventeen seismic-refraction surveys were conducted, generally along lines of equal elevation, to determine (1) depth to bedrock or weathered bedrock; (2) depth to water table, if present; and (3) depth to intermediate weathering zones within the saprolite and/or weathered rock. A signal-enhancing 12-channel seismograph was used in conjunction with an array of 12 geophones. The energy sources used were blows from a 3.6 kg (kilogram) sledge hammer on a steel plate and a seismic shotgun using 8- and 12- gage shells. Seismic data were analyzed using the delay-time method and a ray-tracing procedure (Scott, 1977).

Aerial photographs for seven different years between 1936 and 1988 were examined for this study. More than 170 landslides identified on these photographs were mapped on topographic quadrangles and then field checked (fig. 1)(Guariguata and Larsen, 1990). After field work was completed for this article, Hurricane Hugo struck eastern Puerto Rico in September 1989, with maximum sustained winds of over 225 km per hour. The 3-day rainfall total associated with the hurricane ranged from 165 to 344 mm. More than 200 landslides occurred within and near the CNF during this storm; most of these were shallow soil slips, as well as shallow earth slides and

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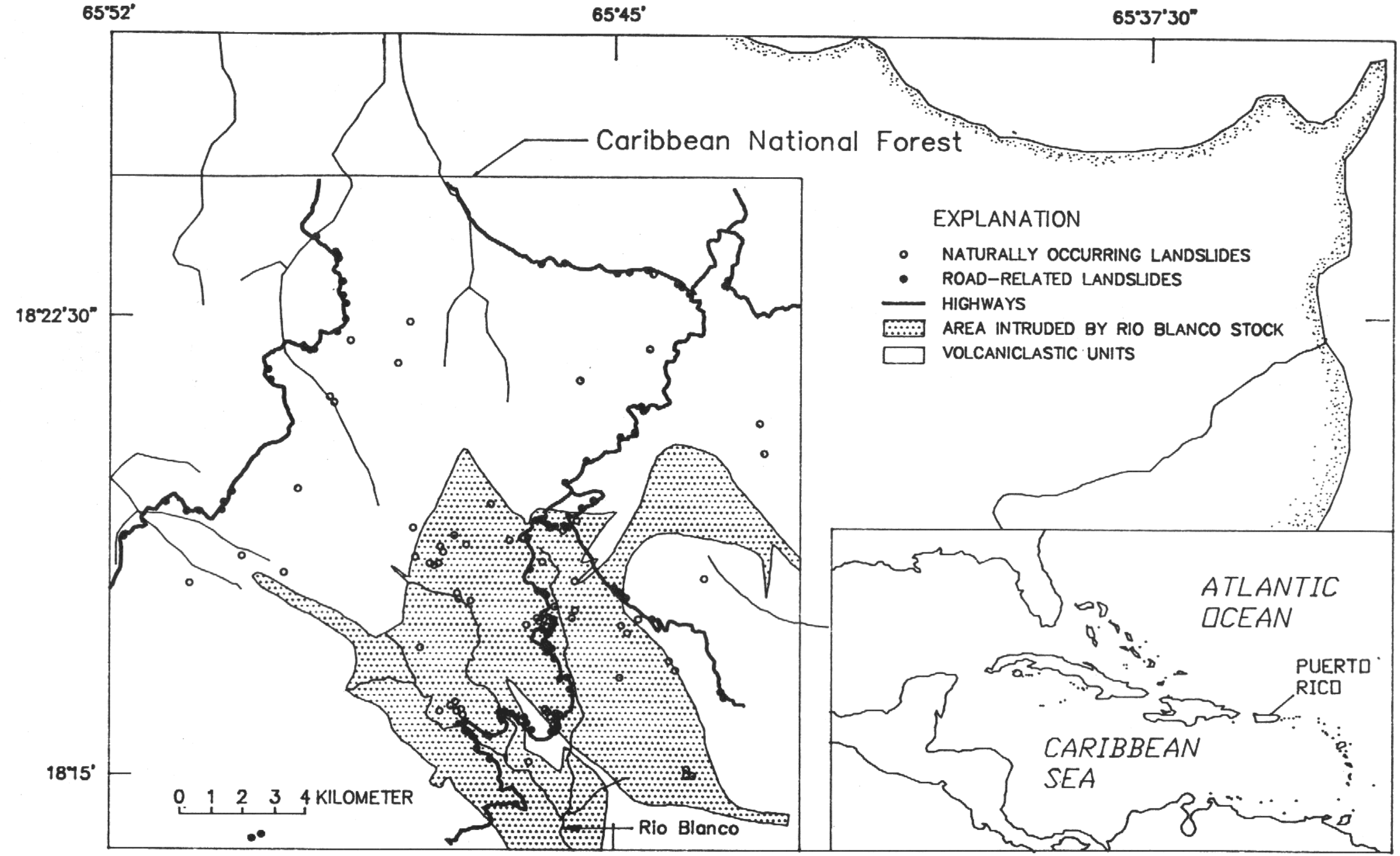

Figure 1. Map showing location of landslides in the Caribbean National Forest (from Guariguata and Larsen, 1990).

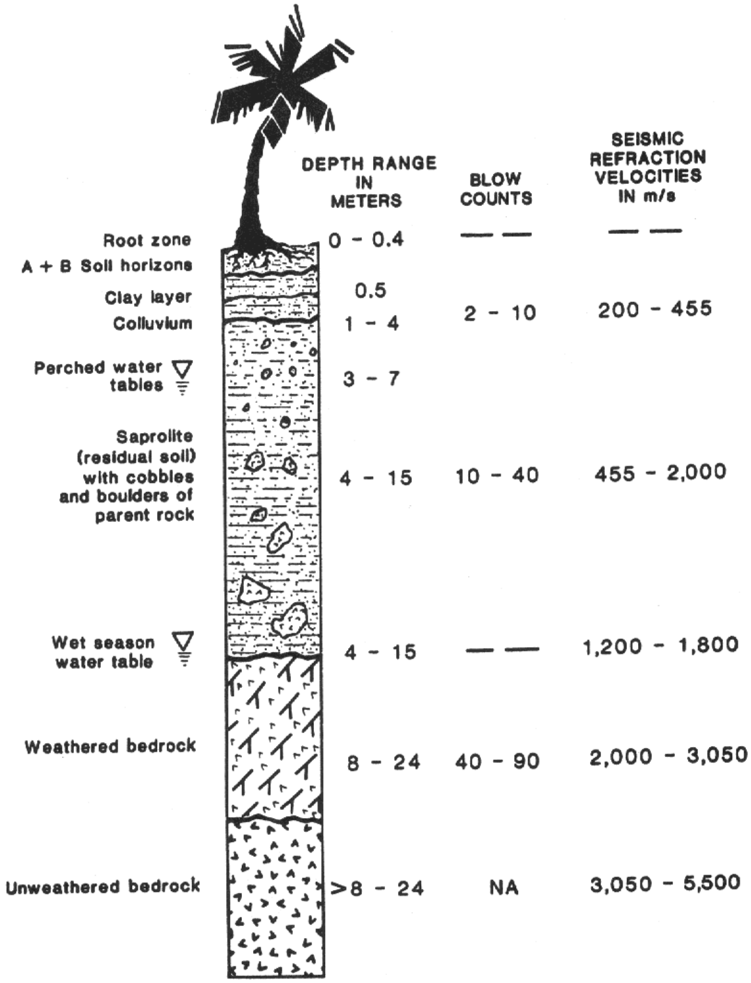

Figure 2. Generalized stratigraphic column for the Caribbean National Forest.

debris flows (Larsen, 1990). These recent landslides are not included in this study.

RESULTS

In the soils overlying quartz-diorite bedrock, friction angles obtained with the BST range from 5.3 to 39° and cohesion values range from near 0 to 21.4 kPa (kilopascals) (fig. 3a,b). The data are sharply skewed towards low strengths and generally indicate soils of low cohesion (mean cohesion was 6.29 +/- 1.59 kPa). Soils overlying volcaniclastic bedrock tend to have greater mean cohesive strengths (9.35 kPa) but a friction angle range (11° to 38°) similar to that of soils overlying the quartz-diorite bedrock. Although friction angles for both soil types do not differ significantly, the frequency distribution of friction angles for quartz-diorite soils shows a marked skewness for higher values (fig. 3a). Friction angle data for volcaniclastic soils are more equally distributed (fig. 3a). Cohesion values for the two soil types show higher values for those soils overlying volcanic bedrock (fig. 3b). Saprolite above and near headscarps is considerably drier and is subject to tensile stresses, (mean of -4.9 +/- 0.7 kPa) (Simon and Larsen, 1988). Tension cracks are visible at some sites, particularly those that have had recent landslides. These tension cracks provide avenues for rapid infiltration of rainwater into the subsurface, which thus increases the potential for more rapid saturation and the build up of pore-water pressure.

On the basis of field observations, lithologic data, and seismic velocities, substrate materials fall into three general categories, outlined in figure 3. Unsaturated soil, colluvium, and upper-saprolite materials have a mean seismic velocity of 476 +/- 127 m/s (meters per second). The lower saprolite, which includes denser, clay-rich, less-permeable zones, has mean seismic velocity of 1,420 +/- 157 m/s and ranges from 4 to 15 m below ground surface (Larsen, 1989a, 1989b). Where drilled, the clay-rich layers show a 2- to 3-fold increase in blow counts [Blow count is an engineering term which describes the number of blows required to drive a drill-rig sampling spoon a distance of 30 cm (centimeters) with a 64 kg hammer falling 76 cm]. At several sites, a perched water table was encountered at the top of these clay-rich horizons. Bedrock mean seismic velocity is 3,930 +/- 1625 m/s. Average depth to bedrock is 15 m, but this depth varies from 8 to 24 m because of undulating bedrock weathering-surfaces, formed by uneven weathering rates.

Field examination and testing of exposed relict structures in saprolite using a pocket penetrometer reveal black, clay-rich layers several centimeters thick having higher density and strength [average values for unconfined compressive strength of 3 kg/cm^2 (kilograms per square centimeter) as compared with 1 kg/cm^2] than the overlying saprolite. Chemical analyses of these black layers in saprolite from Georgia and Puerto Rico indicate that the dominant component is manganese oxide, with iron oxide and humic compounds also present (St.

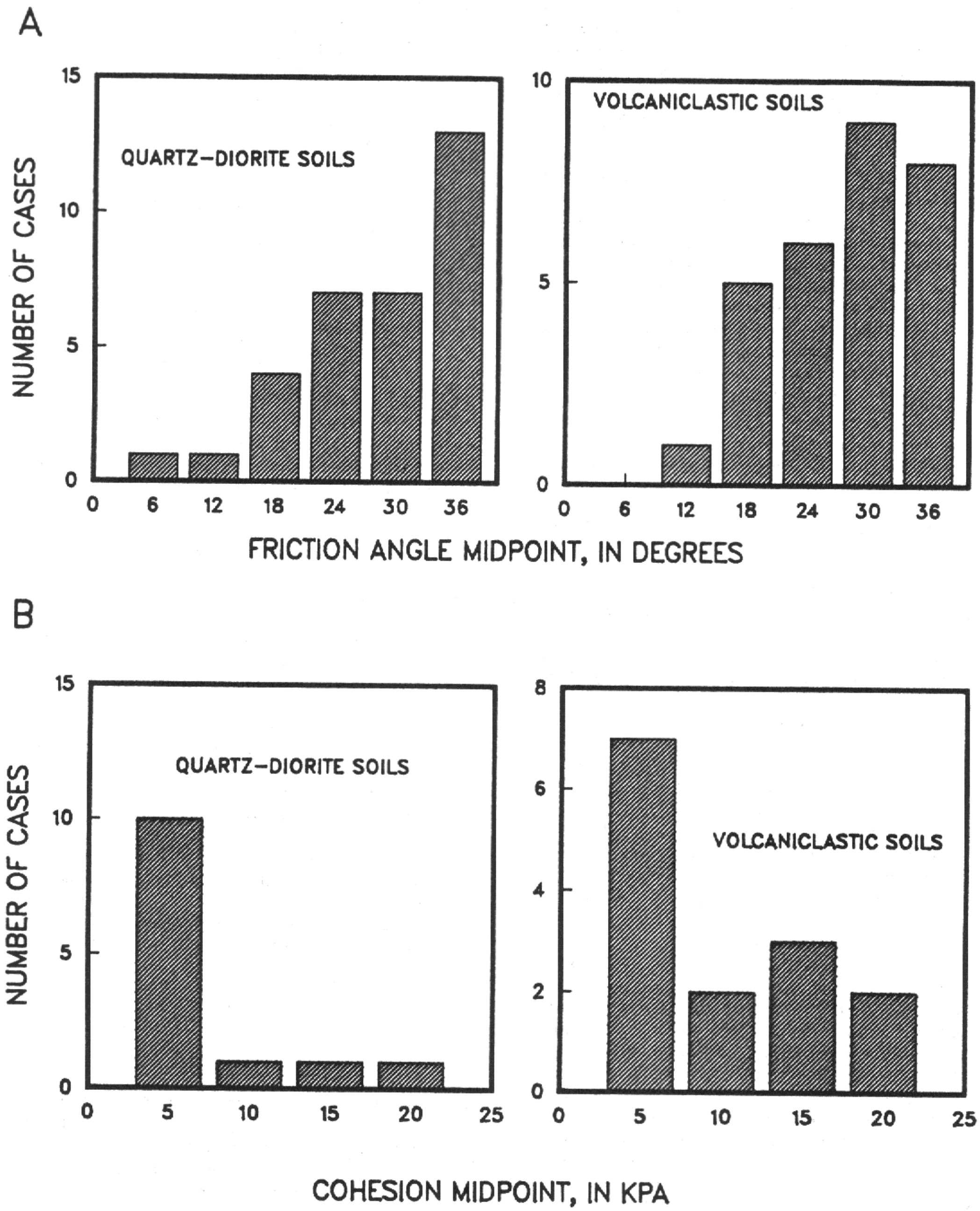

Figure 3. Frequency distribution for (a) friction angle and (b) cohesion in soils overlying quartz-diorite and volcaniclastic bedrock.

John and others, 1969). Discontinuous zones of this material generally are associated with perched water and increased pore-water pressure during and after intense and prolonged rainfall. This implies that smaller landlides within the saprolite probably occur along zones of increased pore pressure immediately overlying saprolite layers having decreased permeability and increased density.

Data from five drill-holes that encountered water show two perched water tables at depths of 9 and 12 m at the lower segments of slopes. These depths, noted during periods of wet-season (June to November) normal rainfall, are several meters deeper than most observed landslide failure planes. Preliminary piezometer data from recent storms of small to moderate rainfall accumulation and intensity indicate a significant water-table rise often occurs within 1 to 5 days after the storm. One such storm (Hurricane Hugo) triggered numerous landslides with failure planes that are 0.5 to 2 m deep, presumably the depth of a zone of increased pore pressure (Larsen, 1990). The largest landslide that resulted from Hurricane Hugo, a 23,000 m^3 debris avalanche, occurred three days after the passage of the storm.

Preliminary field and air photo surveys of recent landslides and adjacent areas reveal trends in landslide type, location, dimensions, relation to highway construction, timing in relation to intense rainfall, apparent failure mechanisms, and failure planes. The majority of landslides observed in the CNF are shallow soil slips, earth slides, debris slides, and earth slumps which occur mainly along planar or concave slopes (classification after Varnes, 1978; Campbell, 1975). They commonly are from 0.5 to 7 m deep, are tens of meters long, and range from 5 to 25 m wide. Also present, but less common, are debris avalanches as well as rock falls and slow earth flows found mainly along roadcuts. More than 60 percent of the mapped landslides are associated with highway construction (fig. 1).

Once initiated by buildup of hydrostatic pressure within tension cracks, earth slides commonly fail along planes of weakness in the saprolite. These planes of weakness are former fracture or joint planes that remain evident in the saprolite after the rock has been weathered. Because stress-release fractures that form in parent rock as it weathers generally are parallel or subparallel to the slope surface, the fractures provide an optimal orientation for a sliding mass. Other evidence of earth slides are trees rafted downslope in upright position on intact blocks of soil. Since the majority of the forest root zone is less than 40 cm thick (Brown and others, 1983), these trees continue to grow at their new location, which contributes to the forest canopy recovery.

Evidence from headscarps and exposed unweathered, or slightly weathered, bedrock on failure planes indicates that the largest landslides (areas greater than 20,000 m^2) usually start as slumps and fail along the saprolite/bedrock boundary. Several such landslides, located along a CNF highway, are 300 to 600 m long and become debris avalanches downslope with long and narrow run-out zones. They are all located above roadway sections where slope toes were removed, and all occurred during or shortly after hurricane-related rainfall.

Most landslides (54 percent of road-related and 77 percent of naturally-occurring landslides) are within the area of the quartz-diorite intrusion which indicates a strong lithologic control (fig. 1)(Guariguata and Larsen, 1990). Landslides associated with road construction are almost exclusively on slopes subjected either to toe removal or to surcharge by fill material on their upper segments.

Most of the dated landslides can be associated with specific storm events in which one-to five-day total rainfall ranged from 100 to 1000 mm. Actual timing of the landslides cannot be determined in most cases due to their remote location. For most known cases, the failures occurred within several hours to 5 days after the rainfall. A notable exception is one of the largest landslides, a 300,000 m^3 debris avalanche which occurred five weeks after the passage hurricanes David and Frederick in 1979. These hurricanes struck the island within a period of five days and each produced more than 300 mm of rainfall. This indicates that slow infiltration of rainfall (over a period of five to six weeks) may have resulted in pore-pressure buildup along deep failure surfaces and the subsequent large landslide.

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